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Energy in the urban water cycle: Actions to reduce the total expenditure of fossil fuels with emphasis on heat reclamation from urban water

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ABSTRACT

In the urban water cycle, water supply, transportation, treatment and disposal are services that consume a considerable amount of energy. This paper reviews and summarizes state of the art measures applied in different parts of the world to reduce the energy consumption related to urban water. Based on a literature review, an overview of the energy balance in the urban water cycle in some regions of the world is presented. The balance shows that water heating is the largest energy expenditure with approximately 80% of the total primary energy demand in the residential sector of the cycle, while the remaining 20% of energy is spent by waterworks on pumping and treatment. Examples of measures to reduce the consumption of energy are presented according to a philosophy of actions in order to achieve energy efficient processes. The emphasis is on technologies and case studies to recover the energy from urban water, as well as some factors that influence the deployment of the technologies.

Contents

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1. Introduction

The water cycle of an urban zone starts with the abstraction of water, followed by its transportation, treatment and distribution to the end-user. Once water has been used, water is collected, often mixed with rainwater run-off and transported to a wastewater treatment plant (second treatment). Treated water is, in some cases, reclaimed for reuse, but most frequently discharged to the surface water. After this last stage, water comes into contact with the natural water cycle and eventually, it will return to the urban zone closing the urban water cycle (UWC). The UWC thus comprises water catchment and withdrawal, drinking water treatment, distribution, water use, wastewater treatment, recycling and rain water [1] and can be divided into three main categories: before, during and after use (drinking water, tap water and wastewater respectively). The initial and final characteristics of water differ in each stage; so does the type of energy required during its handling. Fig. 1 shows the main energy types involved in each stage of the main categories. Negative and positive signs correspond to energy expenditure or gain respectively. For drinking water production (stages one to three) energy is mainly required for pumping. In addition, there is indirect, energy burdens in the production of chemicals required for the treatment. During water use (stage four), energy is used for water heating. Stages five to eight denote the category in the UWC related to the management of wastewater. In stage seven (wastewater treatment), thermal and electrical energy can be recovered from the chemical energy (biogas from digestion of organic compounds) in wastewater.

In order to make urban zones more sustainable, infrastructure changes aiming at energy neutral activities are required. A concept that has been developed to strive to zero net energy consumption is called “Trias Energetica” (a brief description can see seen at www.triasenergetica.com, Entrop and Brouwers [2]). It suggests three directives that can be followed successively or in parallel to promote energy savings and avoid the use of fossil fuels. These directives are: (1) Reduction of energy demand by avoiding waste and implementation of energy-saving measures (prevention). (2) Replacement of fossil fuels by renewable energy sources (RES) whenever it is possible. (3) Efficient use of fossil fuel and its reuse (efficiency).

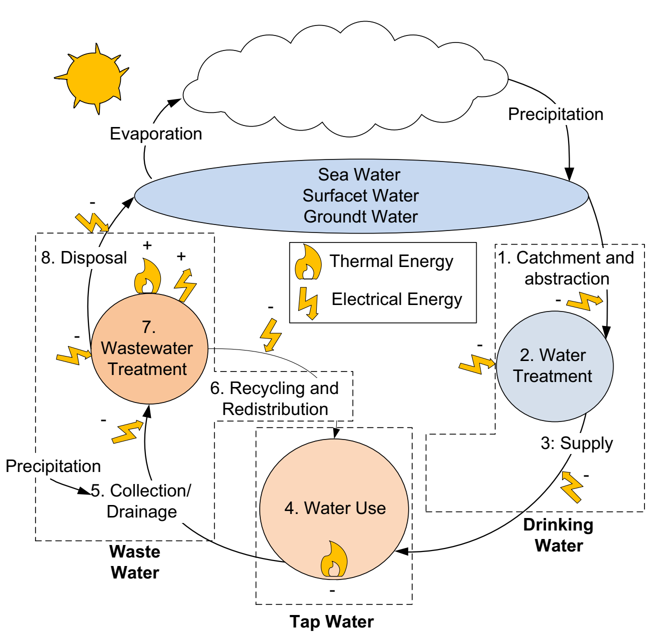

Fig. 1. Energy involved in different stages of the UWC. The main categories according to water use are denoted by dotted squares.

This paper describes state of the art measures, applied in different parts of the world, to reduce the energy consumption in the UWC. Chapter 2 starts with an inventory and compares information on the energy balance in the UWC, to identify the largest energy expenditures. The third chapter addresses some examples where the energy expenditures in the UWC were reduced. The fourth chapter provides a description of technologies and case studies related to efficient use of fossil fuels. The fifth chapter describes factors that influence the feasibility of heat recovery systems. Discussion and conclusions from the review are presented in the last chapters of the paper.

2. Energy in the urban water cycle

2.1. Energy consumption for drinking water production

Different factors such as the distance from the water source to the consumer, water abundance, initial quality, and required treatment for use determine the overall energy expenditure per volume unit of water in the UWC [2]. In the first stage of the UWC, water must be abstracted, and transported for human use. In this stage electricity is the main energy source. In addition, there is an indirect energy use for the production of chemicals.

A life cycle assessment-based research was performed by Racoviceanu et. al. [3] for the operation of the water facilities in Toronto. The authors found out that electrical energy needed for pumping accounted for 94% of the total energy burden and for 90% of the total CO_2 emissions, while the energy burden related to the production of chemicals and transportation (of chemicals) accounted for only 5%. The city spent 1.4 pJ of delivered energy on water pumping in 1998; approximately half of the pumped water was drinking water which accounted for 0.75% of the delivered energy to the city [4]. Depending on the availability of water sources, the share of the required energy for water supply can increase. For example, 5 % of the total electricity use in California is required for water supply to the state, where 4.3 % is used for transportation and the remaining 0.7 % is used for treatment and distribution [5].

2.2. Energy consumption during water consumption

In the state of California, although the electricity expenditure for water supply is the largest electricity consumer, the electricity used for water heating in the same state reaches 14% of the total consumption [5]. The purposes of water use in the residential and commercial sector are limited; most of them are related to cleaning purposes. Applications can be divided into eight main activities of which toilet flushing and showering represent the largest tap water expenditure in households, the latter usually being heated before its use [6]. According to results shown in a survey in the USA, approximately 150 L/cap of water were heated from 13 °C (average tap water temperature) to 40 °C [7]. Taking into account that in the USA 40% of the residential water is heated with electricity, the efficiency factor of electric (0.9) and gas heaters (0.82), and the efficiency factor to convert primary energy

to thermal energy by electricity [8], the primary energy consumed for water heating amounts to 13,000 MJ per capita per year. In The Netherlands, this value amounts to 4400 MJ/cap/annum considering that each person heats approximately 68.8 L of tap water in households to an average temperature of 27 °C [9-11]. In both countries showering represents the activity that uses most of the heated water.

2.3. Energy consumption after use

Once wastewater leaves a household, the heat carried with the water diffuses to its surroundings and, when the temperature of the soil is lower (as it normally is), thermal energy in the water decreases. In order to dispose the wastewater, it must be collected and pumped to the wastewater treatment plant (WWTP). The share of consumption in this stage varies according to factors such as level difference in urban zones, precipitation, proximity to the WWTP, type of sewer (combined or separated) and population density. In Sydney, the percentage of energy consumed in sewer systems is close to 7% of the total energy spent in the UWC [12], while in The Netherlands, the percentage is approximately 10% [13].

In the WWTP, aeration in aerobic treatment processes can account for 1.8 MJ/m^3 to more than 3.6 MJ/m^3 of electricity depending on the type of biological system [14]. A study of almost 1,000 wastewater treatment plants in Japan focused on determining the specific energy consumption for wastewater treatment. The range of energy consumption was 1.0 to 7.5 MJ/m^3 and in most of the cases, biological treatment represented half of the total operating costs [15].

Biogas is the most common form of energy that is recovered from wastewater. The potential energy harvested from biogas recovery in wastewater treatment plants is estimated to be about 360 MJ (100 kW h) of electricity and 777 MJ of heat produced with the help of combined heat and power units for every 45,000 inhabitants with an average water consumption of 380 L/cap*day [16].

2.4. Comparison of energy balances for different case studies

Table 1 presents the comparison of energy use in the UWC for different regions. Water before and after consumption requires about 20% of the total primary energy in the UWC. In the case of the USA and the Netherlands, the primary energy used for water heating in the residential sector accounts for more than 80% of the total consumption. Similar percentages have been found in Taiwan where 84.5 % of the energy spent in common buildings is used for water heating in showers and food preparation. The rest (which corresponds to 8.46 kJ/m^3 of primary energy) is spent on treatment and transportation of water and wastewater [17]. The numbers correspond to previous studies [11,18,19] which also suggest that heating is the most important energy input in the UWC.

Production of energy is highly related to the emission of greenhouse gases which is considered as an accelerating factor for climate change. The primary energy per capita consumed in the UWC (Table 1) multiplied by an emission factor, corresponding to the type of delivered energy, results in the amount of emitted greenhouse gases. It must be considered that biogas (mainly methane and carbon dioxide) is produced during the biological treatment of wastewater. In the Netherlands, assuming that almost all biogas is completely flared, every person produces annually 324 kg CO_2 eq. by using the UWC (Table 2). This amount represents 3.14 % of the total CO_2 emission per capita [20]. Frijns et. al. [21] estimated that the contribution of CO_2 emissions from waterworks and the overall UWC were 0.8% and 3.3% respectively. In regions where the gas is not flared the mass of emitted methane would contribute to the greenhouse emission even more, since methane has 21 to 23 times higher greenhouse gas effects than CO_2 [22].

The numbers in Table 2 do not consider gases produced in the sewer network which are not captured or treated in most places in the world. For the case of gases produced inside sewer networks, Guisasola et. al. [27] have determined that the emission of methane in sewers could have a comparable greenhouse gas effect to that produced in WWTPs. Measurement results of greenhouse gas production in sewer systems of Amsterdam suggest a similar conclusion [28]. Furthermore, an experiment that traced the carbon isotopes in four treatment plants in Australia, showed that fossil organic carbon contributes for 4 to 7% to the total carbon balance from domestic wastewater [29]. According to Washington et. al. [30], in order to mitigate half of the effects of Climate Change, a global reduction of 70 % in the emission of greenhouse gases must be achieved by the year 2100, which implies that activities involved in the UWC must be improved.

3. Actions to reduce the energy expenditure in the UWC

3.1. Prevention of energy use

In agreement with Sala and Serra [31], the reduction of energy demand would begin with the protection of water sources, enforcement of water savings and water reuse, since the energy expenditure needed to pump or heat water is related to the amount of handled water. On a household level, there are documented cases where the use of water-efficient appliances has reduced water demand in urban zones. After four years of

Table 1
Primary energy consumption in stages of the domestic urban water system [MJ/cap/annum]. delivered energy was converted into primary energy taking into account conversion ratios [3,23].

Category	Reference Place Population, million	[13,19] Netherlands 16.6	[24] USA 296	[25][a1] Walloon region 3.4	[3] Toronto 2.5	[12][b1] Sydney 4.4
Before consumption	Water Catchment	301	474	123	177	[–]
	Water Treatment			55		107
	Water supply and distribution	60	843	137	404	348
During onsumption	Water use	4400	13600	No data available	No data available	No data available
After consumption	Collection and transportation of wastewater and other water*	105	530	0[a2]	380	74
	Wastewater treatment	476		176		434

[a1] Population was obtained from http://statistiques.wallonie.be (2009), leakages and water exports to other regions were taken into account.
[a2] Energy for collection was considered negligible since most of the sewer is driven by gravity.
[b1] Water consumption per capita was obtained from www.sydneywater.com.au (2010).
* Other water refers to industrial and rainwater treated in municipal WWTP.

Table 2
Annual eq. CO_2 emitted per person by domestic water use. Factors correspond to CO_2 emission by electrical production, hot water heating and biogas burning in The Netherlands [19,26].

Category	Stage	Primary Energy, MJ/cap/a	Type of Energy	Emission Factor, kg CO_2 eq./MJ	kg CO_2 eq./cap/a
Before consumption	Water catchment Water treatment	301	Electricity	0.0689	21
	Water supply and distribution	60	Electricity	0.0689	4
During consumption	Water use	4400	Natural Gas	0.0567	249
After consumption	Collection and transportation of wastewater and other water	105	Electricity	0.0689	7
	wastewater treatment	476	Electricity	0.0689	33
	Biogas production during treatment	110	Biogas	0.0842	9

implementing a water reduction program in one of the largest counties in Florida, USA, the single change of any hot water demanding appliance (shower head or wash machine) reduced the water demand by 10.9 and 14.5% respectively [32]. In Sydney, Australia, the results of a large program where changes of head showers, installation of tap flow regulators, improvements in toilets, detection of leakages and water consumption advice were performed in approximately 200,000 households, indicate that the reduction of water consumption reaches 12% for indoor use [33].

On an urban zone level, demand management could reduce the volume of water consumed in a region and subsequently decrease the energy needed to operate water facilities without major changes in infrastructure. Vairavamoorthy et. al. [34] enumerate some techniques to manage the demand in distribution networks and, with the help of a case study of a distribution network in India, they conclude that, by following the guidelines for demand management, it was possible to improve the supply for consumers without increasing the volume of water to be supplied. Minimization of leakages could help to improve water conservation. Kumar and Karney [35] estimate that 13% of the water loss by leakage could represent about 10 to 20% energy losses in pumping and treatment.

3.2. *Use of renewable energy sources*

The use of RES in the UWC relates to two different concepts that are often confused. The first concept concerns the use of energy from renewable sources to substitute energy from fossil fuels during the UWC operation. Green power purchase by waterworks is one type of practice (and often the easiest to implement) to substitute energy from fossil fuels [36]. In most cases, the use of renewable energy is realized by buying certificates that guarantee that part of the electricity supplied by the grid was produced from RES.

Energy from RES can also be used directly when water is used or treated. Solar collectors or heaters are an example of technology that has substituted energy from fossil fuels in the UWC. Balaras et. al. [37] estimate that, depending on the ambient conditions of a region, the use of solar collectors could reduce the energy consumption in buildings by 60 to 80% compared to electric heaters. Michopoulos et. al. [38] compared energy savings when renewable energy sources were applied for ambient heating and hot water production in a conventional house located in northern Greece. With renewable energy, there was overall electricity saving of 54% during a year period. The use of renewable energy sources for water heating has not widely been adopted. Leidl and Lubitz [39] consider that the implementation of heating technologies in households has been hindered by insufficient awareness, lack of experience and insufficient information on the performance. The authors further suggest that, in addition, financial incentives are needed to facilitate a large scale roll-out of renewable heating systems in medium-sized North American communities.

In water treatment, much effort has been put in research into the desalination process where energy consumption in large reverse osmosis treatment facilities can reach up to 7-22 MJ/m^3 (2-6 kWh/m^3) [40]. Mathioulakis et. al. [41] have discussed the characteristics of different desalination processes driven by renewable energy sources suggesting that amongst other solar-driven processes (such as dehumidification, reverse osmosis and electro-dialysis with photovoltaic and wind power), membrane distillation seems to be an adequate technology that can be implemented in warm climates and at locations with waste heat sources such as cooling water (often warm brackish water) from industrial sources. Nevertheless, membrane distillation has not been widely applied in practice yet. In some documented cases of full scale applications, the major reported problems relate to the membrane (fouling) and plant lifetime [42]. Although thermal desalination is a higher energy consuming treatment process, this technology has become a suitable option for decentralized facilities in remote locations of high solar intensity [43]. Solar photocatalysis for advanced water treatment and disinfection is also a technology currently under development, suitable to substitute fossil energy sources [44]. However, the high price and low yield of delivered energy compared to conventional energy sources is still a barrier for applying these technologies on a large scale. Besides, the fluctuating generation profile of renewable energy sources such as wind and sun makes it difficult to use them for base-load supply and, in most cases, energy storage facilities have to be considered during the design of such systems.

The second concept visualizes the UWC as a source of renewable energy since water and wastewater are a carrier of diverse types of energy [45]. Potential energy from the UWC, for example, can be recovered with hydropower. The effluent of a WWTP in Warendorf, Germany was used for this purpose; a water wheel (4.83 m diameter, 1.5 m width, 40 plates) was installed in the effluent of a municipal WWTP to drive a generator to produce electricity. Annually, the energy output varied between 30 and 144 GJ [46]. Ramos et. al. [47] mentioned that the efficiency of using pumps as turbines to regenerate electricity could be near to 85%. However, these systems can only be installed in places where there is a level difference between the stream and the turbine and enough flow (at least 5m of head and a flow rate of 2m^3/s) to make a project economically feasible.

So far, the most important energy source, contained in wastewater, comes in the form of biogas. When biogas is recovered from anaerobic digestion of sludge, electricity and heat can be reclaimed by means of combined heat and power units (CHPs). The heating value of biogas (23.3 MJ/N m^3 [48]) can produce electricity and heat with a combined efficiency close to 95%; which is the reason why this technology is probably the most wide spread method to

harvest electricity and heat simultaneously. The average energy yield of anaerobic treatment is 13.5 MJ of energy as methane/kg and when this energy is converted into electricity and heat, the electricity output (assuming a conversion efficiency of 40%) is 5.4 MJ (1.5 kW h) [49]. Horne et al. [3] show diverse case studies where energy was recovered applying CHP units in the USA.

The success of biogas production as an alternative method to reduce fossil fuel consumption is linked to the variety of usable sources for its production, the capability to produce it in small and large quantities and the availability to use the types of produced energy (heat, steam, electricity, hydrogen) in different applications [50]. One example of the flexibility of sludge digestion process is described by Schwarzenbeck et al. [51]. The authors documented a case in Germany where a WWTP is using its digesters to treat skimmed fat from a dairy together with the activated sludge produced in the aerobic treatment. Before the treatment of the fat, the WWTP was purchasing more than 80% of the energy with one digester, but with the addition of a second digester and the treatment of fat, the plant produced 100% of its own energy needs and sells the surplus (approximately 10%).

After biogas production, the digested sludge volume is reduced. In the EU, approximately 10 million tons of dried solids are produced annually. The production of biogas reduces this volume up to 60% [52]. The incineration of dried sludge obtained from the anaerobic digestion is another way to recover energy from wastewater. In Amsterdam, the use of the heat produced by the incinerated sludge avoids the use of 1 million N m^3 of natural gas per year [53].

One technology that promises direct electricity generation during the treatment of wastewater is the fuel cell, especially the microbial fuel cell. The cells can be conceived as bioreactors that can utilize the current generated when microorganisms, in anaerobic conditions, catalyze organic compounds. Aelterman et al. [54] demonstrated in laboratory scale a production of 58 W/m^3 (288 kJ) of electricity, when microbial fuel cells were applied to treat wastewater. In relation to the quality of the produced effluent, microbial fuel cells have been able to reduce 8% of initial chemical oxygen demand at a hydraulic retention time of 33 h [17], although a large fraction of organic matter was removed without the subsequent production of energy. Because the electricity that can be extracted from microbial fuel cells is still lower than the amount that can be extracted with combined heat and power, Pham et al. [55] consider that the future of anaerobic digestion and microbial fuel cells will be complementary. The former will be able to treat highly polluted wastewater at temperatures near 30 °C; microbial fuel cells will be able to treat water with low concentrations and at low temperature. Microbial fuel cells have not been developed commercially, mainly because of scale-up and operational problems. The required area for the electrodes still poses a technical problem when fitting in small reactors. The materials of the electrodes have decreased significantly in price although they are still high. In addition, there are problems in continuous-mode operation and changes in substrate and temperature affecting the process [56].

Nevertheless, the chemical energy contained in wastewater that can be extracted represents from 0.25 to 0.5% of the total primary energy consumption in developed countries, even though its utilization could reduce the carbon footprint of WWTPs if this energy were reused [57]. Funamizu et al. [58] estimate that the chemical energy converted to work obtained in a WWTP in Japan, represents near one fifth of the total energy contained in wastewater if heat is taken into account. The remaining energy (80%) stays in form of sensible heat. Ways to recover sensible heat will be considered in detail in the following section.

3.3. *Efficient use of fossil fuels*

Automation and control of water treatment facilities is the state of the art method to improve energy efficiency, and nutrients removal without affecting the effluent quality. In conventional WWTPs, aeration is the most energy demanding operation. For 35 days Ingildsen et al. [59] tested a dynamic control in a WWTP where the aeration of the mixed liquor was controlled by an online monitoring of ammonium in the mixed liquor tank and the effluent from the clarifiers. Although it was not possible to quantify with accuracy the energy saving because of technical problems during the test, it was shown that energy for aeration could be reduced from 5 to 15%. A similar optimization technique based on aeration control by ammonium concentration was put into practice in two WWTPs in Switzerland. In those cases, other site-specific automation and control strategies were applied together with the control of aeration. After the implementation, it was estimated that energy savings ranging from 16 to 25% were achieved [60]. In another study, Baroni et al. [61] developed and patented a fuzzy logic control system for the aeration in biological treatment. The controller was installed in one of four tanks of a WWTP and tested for one year. The remaining three tanks were operated as usual (with a proportional integral derivative control). The new control could save 4% of the global energy consumption in aeration (15,841 kW h/d) related to mean global energy consumption before the new control implementation (16,506 kW h/d). Although the authors concluded that the optimization cannot be compared because there were two different time periods, the control system substitution of the other three tanks would improve the overall performance of the process since the variability of effluent quality and energy consumption was also improved with the fuzzy logic controller. Concerning pumping, Lutz [62] estimates that the replacement of adjustable speed drivers and other energy saving programs in WWTPs can save 5% of electrical energy.

In a global survey with more than 15 case studies, the Global Water Research Coalition (GWRC) and the United Kingdom Water Industry Research (UKWIR) identified niches for energy efficiency practices and technologies in water and wastewater facilities. They concluded that pumping is the main energy-demanding operation with more than 80% of the total consumption for water treatment and supply, while aeration was the operation that consumed most of the energy in wastewater treatment (50–60%). In wastewater treatment, pumping accounted with 30% of the energy expenditures [63]. For water treatment and supply they identified 5 to 7% potential improvement in pumping optimization, 3% to 7% energy savings with pump replacements, and 5 to 30% of improvement with the optimization of current operational techniques. In wastewater 25% of energy savings can be reached with improvements in the aerobic treatment; a good control of the process could save 50% of energy consumption. They also found improvement opportunities in buildings inside treatment plants (15% energy savings).

4. Thermal energy in the UWC

In a typical US household, after the air conditioning, the second largest energy consumer is water heating (for ambient heating and use in appliances) with approximately 20% of the total consumption [10]. Hofman et al. [13] estimate that 40% of the total energy losses in modern Dutch houses are represented by hot wastewater leaving the houses. A simulation carried out in order to calculate the benefits of installing heat recovery systems in the metropolitan area of Tokyo to recover heat from all water sources available in the city, showed potential energy savings of 41 pJ annually in the year 2000 [64]. Some actions to improve the energy balance for heating in the UWC deal with the installation of heat recovery system for space heating. This section introduces equipment, case studies and considerations of heat recovery installations in the UWC.

4.1. Equipment used in heat recovery systems

A heat recovery system is a combination of equipment such as heat exchangers, heat pumps and thermal storage. They can be applied in sewers, drinking and industrial water supply networks [65].

4.1.1. Heat exchangers

First, there are heat exchanger types such as shower heat exchangers, which have the distinguishable characteristic that they recover the waste heat almost at the same place where the heat is needed. Shower heat exchangers have a flat shape and are placed beneath the drainage of a single shower. They can also be installed inside basements or service rooms. They can vary from a few centimeters long and 1 cm of diameter, to 1.8 m long and 7.5 cm diameter. These devices are commonly made of copper and arranged in spiral tubes. A common characteristic is that both have no movable parts and the main aspects affecting the efficiency are the place where it is installed (near the drainage, the heater and the tap) and fouling. Optimal places are limited in already existing buildings [66].

A second type of heat exchangers comprises larger devices applied to recover heat from sewers and at the same time they work as sewer pipes. These devices are commonly coupled to heat pumps (heat pumps are explained in Section 3.3.1.2). These heat exchangers can be shell and tube heat exchangers, spiral tube heat exchangers or plate heat exchangers mounted on pre-built pipes or pits which can be placed in existing networks. Some of these heat exchangers are equipped with a mechanical screener to remove solids and avoid fouling due to the solid fraction of water and the formation of biofilms [67], which are the major problems reported in all kind of heat exchangers [68]. Performance indicators of heat exchangers due to biofilm formation will be reviewed in Section 3.4.3.

Fig. 2 presents the main configuration of heat exchangers utilized in water networks. Especially for sewer-pipe heat exchangers, different models have been developed. In accordance with the cross section of the pipe, they can be round, oval or rectangular [69]. Advantages of heat recovery from sewers are the relative proximity of the energy source to the consumers, the widespread network in cities and the heat quality that can be found in wastewater when there is a high density of houses nearby. Normally, the warmest wastewater is found immediately downstream the household where the volume of wastewater is small and intermittent. The installation and operation of such heat recovery systems is considered to be economically feasible from 80 kJ/s of supplied heat [70].

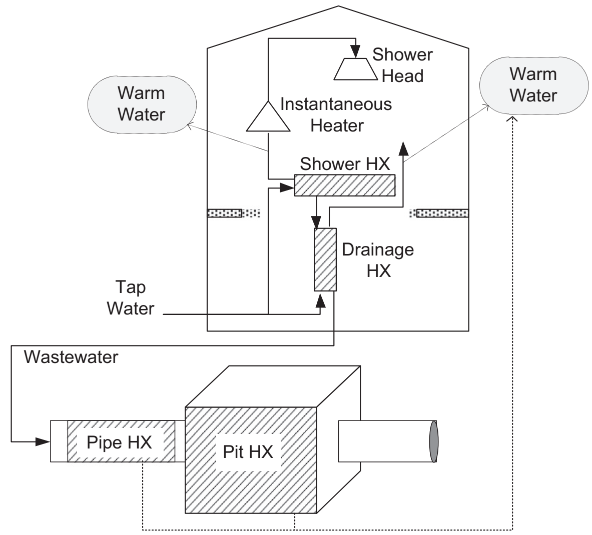

Fig. 2. Heat exchanger types for water networks according to the site of installation. (HX: Heat exchanger).

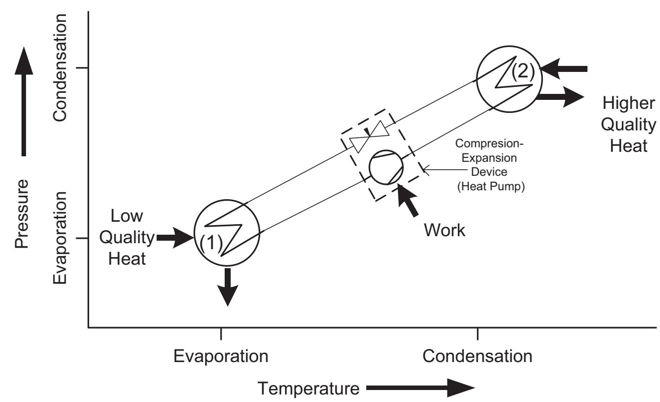

Fig. 3. Basic parts and thermodynamic cycle of a heat pump. Adapted from Holland, Siqueiros et al. [75].

4.1.2. Heat pumps

Heat pumps are devices that transfer heat from a lower temperature to a higher temperature level. Depending on the principle of operation, there are three types of heat pumps: vapor absorption and soli-gas sorption heat pumps, reversible chemical reaction heat pumps, and vapor compression heat pumps [71].

In the first two types of heat pumps, a set of substances that make a reversible (chemical or phase-change) reaction in two stages is required. In the stage called production, the reaction releases heat while in the regeneration stage, one part of the heat pump needs an energy input in order to store heat that will be released again in a new production stage [71]. These devices are used as chillers in industry [72], but there are few publications regarding the use of chemical heat pumps to recover heat from the UWC. Ajah et al. [73] compared chemical and mechanical heat pumps to recover low quality heat from industrial wastewater with similar characteristics to domestic wastewater. The comparison took into account economic, technical, energetic, environmental, and safety aspects. The space needed to install a chemical heat pump was the major constraint in the study compared to the feasibility of a mechanical heat pump.

Mechanical heat pumps are devices comprised by two heat exchangers, a compressor and an expansion valve. They are based on the Carnot cycle where the entropy of a compressed gas or refrigerant is higher causing an increase in temperature. When the compressed refrigerant is warmer, a fluid (water for heating) can interchange the heat inside of a heat exchanger to lower the refrigerant's temperature and then, the refrigerant is expanded causing a further temperature decrease of the fluid. The colder refrigerant can hence interchange heat with a heat source (wastewater or another type of waste heat) to become warmer before it is compressed again to end the thermodynamic cycle (Fig. 3). Classifications of mechanical heat pumps depend on the heat source, the method of expansion and the type of engine: air-source, ground-source, direct-expansion solar-assisted, integrated solar-assisted, gas engine and multi-function heat pumps [74]. Mechanical heat pumps are devices most frequently found in heat recovery systems from wastewater; therefore, in the following, the text will only refer to these types of devices.

The coefficient of performance (COP) of heat pumps is estimated as the useful energy with respect to the employed energy ($COP = Q/W$). The COP is dimensionless, Q is the useful heat (depending on the purpose, it can be for heating or cooling), W

is the electrical energy utilized by the compressor. If the system considers other equipment, such as additional pumps for water conveyance to the heat exchangers, the energy required is added to the denominator. A COP of 4.5 for a heat pump for heating can be considered as very high.

Most of the reports about mechanical heat pumps for building heating come from Europe. In Zürich, the city hall, a swimming pool, the city administration and an already installed district heating network were equipped with heat pumps from 1938 to 1943 with power ranges from 100 to 5860 kJ/s. The heat sources were water from rivers, lakes and industry [76]. Although heat pumps have been utilized for some decades, not many developments have occurred. Alterations in the compression stage (in multi-stages and scroll compressors) and the ejector system have improved their global efficiency to, close to, 35% compared to the firsts commercially available heat pumps [77]. In general, heat pumps are a reliable technology; commercial information published by Mueller [78] mention one facility in Luzern that has been extracting heat from the sewage for more than 28 years without changing important parts.

4.1.3. Thermal energy storage

Thermal energy storage technology can be applied in heat extraction from water to match the heat requirements fluctuations (mostly annually) to the daily fluctuation of heat available from water in households. The working principle is based on the heat capacity of materials (mainly water). The storage can be placed underground or above the ground (thermal storage tanks). Underground thermal energy storage is divided into aquifer thermal energy storage (ATES) and borehole thermal energy storage (BTES). The difference between ATES and BTES is that the second makes use of an arrangement of heat exchangers in such a way that only one well works as the heat source and sink; they are normally applied in smaller projects than ATES, when the soil has a relatively high resistance and can use a coolant to carry the heat in and out the well. An ATES has two wells (a warm and a cold well) separated from each other. It is an open system where the wells are separated by a horizontal barrier or screen (aquifers can be located at the same depth with distance between them or in different depths and closer) [79].

The design considerations of such systems include the required heat interchange, the anticipated levels of stratification in the storage vessels, the heat transfer between the stored water and the environment and the level of insulation of the system [80]. The heat or cold, stored in thermal storage systems, can be stable in time lapses of months. Therefore, they can be used for seasonal storage. In winter, when heating is needed, heat is extracted from the water. The extracted heat is transferred and boosted using a heat pump [81]. In a long term period, the heat extracted from underground thermal energy storage must be similar to the heat carried into the storage, otherwise the temperature of the underground thermal energy storage changes, making the heating/cooling system inefficient. That is the reason why ATES and BTES are usually employed in large buildings where the heat demand is similar to the cooling demand during a year period. For households where the heat requirement is often higher than the cooling requirement, the underground thermal energy storage must be regenerated, i.e. heating the groundwater in summer with the help of a heat exchanger linked to sewer systems [82].

Due to the lower investment costs compared to BTES, the most widely used system for energy storage is ATES.

Because of the abundance of aquifers, ATES is widely applied in the Netherlands. At the beginning of 2005, over 400 projects applying ATES or a combination of cold storage and low temperature heat storage were operational in the country. The largest realized project has a cooling and heating capacity of 19.9 MJ/s for the campus of Eindhoven University. About 45% of the projects concern large office buildings while the remaining percentage is distributed over commercial buildings [83]. The energy savings of ATES compared to traditional heating and cooling equipment can reach 60% [53]. ATES may be coupled to solar heaters or thermal waste energy from industrial sources to store the thermal energy in the underground.

4.2. Thermal energy reclamation case studies in the UWC

4.2.1. Heat recovery before and during water utilization

Few studies have been found concerning heat recovery from drinking water before its arrival to the tap. Possibly, the often lower temperature of tap water makes this source economically less attractive compared to water with higher temperature (such as wastewater). Nevertheless, the importance to extract heat from drinking water might be more related to health issues. If tap water temperature increases in distribution systems, one way to control microbial growth is to lower the temperature of water in distribution systems. In the Dutch Drinking Water Decree [84] the maximum temperature standard for drinking water is set at 25 °C.

One example of heat recovery during water utilization is the use of a heat exchanger for dishwashers. A common dishwasher utilizes approximately 33 L of water from which 22 L leave at temperatures from 30 to 60 °C. De Paepe et al. [85] constructed a 5.5 L heat exchanger with an spiral tube inside (copper, 5400 mm length, inner diameter 9.9 mm, pipe thickness 3.2 mm) to pre-heat water that enters into the appliance with the wastewater that comes from the same dishwasher. Estimating an electricity price of 40 €/GJ at the time the study was done in Belgium, and an annual consumption of 1 GJ (annual average consumption of a dishwasher), the payback period of the heat exchanger would be 6.4 years. The authors mentioned that the cost of materials was 40 € but industrial manufacture would lower the payback period. Larger scale options for energy recovery equipment from wastewater generated by Laundromats were developed in 1984; heating energy (for water and drying) can represent up to 95% of the total energy expenditures in this type of business. Modular heat exchangers were tested to preheat tap water with recovered heat from wastewater. The investment cost for acquisition of the heat exchangers and their installation paid back in less than five years. A survey carried out by Chapin et al. [86] showed that the major obstacle for implementation of such systems was the already installed infrastructure in buildings and the fact that only 14% of laundry managers are owners of the buildings. Therefore, arrangements between real estate owners could inhibit the implementation of heat recovery systems.

For the case of heat exchangers installed beneath the showers, a survey was done in a building where shower patterns of people were monitored. With the help of a Monte Carlo simulation, the researchers concluded that with a heat transfer area of 2360 cm^2, energy savings from 4 to 15% could be achieved in a 3500 inhabitants building located in a city with a warm climate [87], which amount represents from 374 to 1460 GJ/annum. Clogging was the major technical problem encountered during the survey. The largest project mentioned in literature refers to an approximately 400 households system in Oregon, where 200 heat exchangers (Nominal diameter 5.08 and 7.62 cm, 152 cm length) were installed [88]. According to several manufactures, payback periods in multi-family buildings are shorter than in single households because paybacks depend on utilization frequency and cost of installation. The investment can then be recovered from 2 to 7 years.

In another study, a simulation was used to determine energy savings using heat pumps to recover heat from baths in a hotel. The heat was used to substitute base load demand of warm water and space heating. The energy consumption pattern in hotels

(visitors attend mainly on weekends and holiday times) made the use of heat storage tanks necessary. Here the use of a water–air heat pump was more efficient (COP=4.5–5) than a conventional air–air heat pump. The heating system could provide more than 90% of base hot water needs [89].

4.2.2. Heat recovery from the sewer mains, internal streams in WWTPs and effluent

Although the use of heat pumps to recover heat is relatively new in many countries, this heating technology has already been used for some decades. Possibly, the first installed wastewater-source heat pump was in Zürich, at Obermeilen WWTP in 1975 [76]. Perhaps, the largest sewer heat recovery system is operating in Oslo, Norway, where the company in charge of district heating services of the city uses three main heat sources for the delivery of its base-load heat. 8% of the total production is covered by heat reclamation from sewage, which represents an annual energy delivery of 288 TJ (5000 h in use per year). The system was built in an old cavern constructed in 1984. The heat supply network runs in a closed configuration (the heat supply carrier returns to the heat pump to be re-heated [90]). Another system that has a similar configuration was installed to make the Olympic Village of Vancouver more sustainable. In this project, heat is withdrawn directly from the sewer of housing complexes. The heat is extracted from wastewater by means of pit heat exchangers. Screening operations are necessary to remove solids from the sewage. This system covers 70% of the space heating demand of an area close to 558 000 m^2 with 16 000 inhabitants. After the temperature of the wastewater has dropped, it goes to a WWTP located outside of the metropolitan area. Pit heat exchangers were chosen because they offer less restrictions of space compared to heat exchangers located in pipes.

Some estimations about the potential of building heating from wastewater conclude that 3% of the households can be heated in Germany and Switzerland [70]. This low percentage was estimated since only 5% of the sewer network consists of main conduits with steady flow and enough volume to decrease the temperature where practice has shown to be feasible [91].

The internal streams of a WWTP, especially the flows after the aerobic treatment, and the effluent are relatively steady and uniform with a slightly higher temperature than the influent, making them a reliable heat source. Wanner et al. [92], estimate through a heat balance, that the activated sludge in a WWTP can be 0.7 °C warmer than the inflow taking into account the heat introduced by blowers, metabolism, the supernatant return and evaporation. Other reasons are that the efficiency of heat recovery systems from treated water can be higher compared to raw wastewater since fewer nutrients contribute to biofilm formation, the fat and grease content in treated water is slower and heat recovery after the aerobic treatment would not affect its performance. The performance of WWTPs with colder influent is

Table 3
Selected case studies where heat was recovered from the sewerage network, the influent or the effluent of a WWTP.

Reference Country	[94][a] Germany	[58] Japan	[95] Germany	[96][b] Switzerland	[69,97][c] Switzerland	[98][d] Switzerland
Sewer Heat Exchanger						
Source	Sewer	Influent	Sewer	Effluent	Sewer	Sewer
Type	Pipe [e]		Pipe (oval)		Pipe	Pipe
Cleaning system	Flush	Strainer	Flush			
Flow, L/s	8.3–130	136–290	40	10	105	91
Diameter, mm	See [f]		1067 × 1600		1500	
Length, m	20–102		23		200	26
Initial sewer temp, °C		25*	012–022	> 12	10.0–20.0	
Final sewer temp, °C		30*	10.5–21.5	18–23	2C	
Energy extracted, kJ/s	23–150			6.0–30.0	850	44
elements length, cm	100		76	4500		
Yield, kJ/s/m^2	1.8				4.2	
Heat transfer area, m^2					200	18.7
Heat Pump (compressor)						
Compressor power, KJ/s		468			1250	64
Working time, hr/annum			5000			
COP heating		3.8*		4,0–3,0	3,1	
COP cooling						
Distance to consumer, m	160–102		160	1500		
Heat output, kJ/s	12–200	1140	32	5600*4300**	350–450	34
Base load heat, %			25	50–30	33	32
Heating Network						
Use	H	H&C	H	H&C	H&C	H
Area, m^2		175400		2500***		
Network Length, m		500			1300**	
Extra Equipment, kJ/s				20	68	
COP total		3.8	03,0–4,0	3,0–4,0		

For cooling raw wastewater to store heat in a Tank, the temperature difference for heating is 8°CH: Heating; C: Cooling.

[a] Comments: Compilation of nine case studies. Peak capacity of heat pump: 7 MJ/s for cooling, 15 MJ/s for heating, the system has three additional storage tanks. The payback period ranged in 8 to 12 years.

[b] The system is probably the largest ammonia heat pump in EU, it was financed by contracting, the output temperature can reach 65 °C.

[c] Estimations of potential calculate that 7500 apartments.

[d] The installation of a heat pump system was 5% higher than conventional heating.

[e] Oval, Rectangle and round plate heat exchanger.

[f] Oval profile: 1600 × 1067–1200 × 800; Rectangle: 1200 × 700; Round: 400–1500 (diameter).

* In heating operation.

** In cooling operation.

*** Approximate number.

elaborated on in Section 3.4.2. Funamizu et al. [58] described the heating system for offices inside a WWTP which uses the secondary and tertiary effluent of the same plant. In this case study, the WWTP took advantage of the short distance between the heat source and the delivery site inside the same plant.

In Switzerland, there are about 20 WWTPs which use the heat of treated water for district heating and cooling [70]. Although many more examples were found (more than 50), the technical information about projects was relatively similar. Therefore, a summary of representative studies where heat is recovered from the influent and effluent of a WWTP, are summarized in Table 3.

Some other uses of heat from treated water found in literature are:

1. Snow melting. Funamizu et al. [58] mentioned some case studies in Japan, where the snow collected in streets is transported to facilities such as the equalization tanks (in summer) for rain water and yards to be melted by treated water. The combined runoff is then returned to the treatment plant for treatment. With this technique, the volume of wastewater added by the melted snow is less than 10%.
2. Use of treated water as coolant. One water treatment facility in Maine (the northeast of USA) utilizes a heat pump in the effluent to avoid the freezing of the disinfectant storage building. The cold weather and problems related with the prepaid fuel provided by a company that went bankrupt, encouraged the treatment facility to use the effluent as a source of heat. The effluent has an average temperature of 15 and 3 °C are taken with the heat pump. The COP of the system is approximately 3.0 and the payback period of the investment was calculated to be 5.8 years [93].
3. A source of heat for sludge drying. The effluent of a WWTP in Germany (Hayingen) is the source of heat for a sludge drying system using solar dryers and heat pumps. The solar dryer system could not be installed as the only source of heat due to the variable availability of solar energy throughout the year. Therefore, a heat pump system was installed. According to commercial information (www.huber.de, retrieved in December 2012) the plant can treat 440 t/annum of sludge with approximately 22% of dry solids.

4.3. Heat recovery from other water sources

In Malmo, Sweden, an area of buildings (85 000 m^2) is heated with heat from the sea and ATES systems (40–70 m depth, average temperature: 10.5 °C). The heat recovery system can be used for heating and cooling. In this second operation mode, the heat inside houses is released into the sea water [99,100]. In The Hague, the Netherlands, a renovated district close to the sea uses thermal energy extracted from the sea to heat 789 homes as well. The system started to operate in January 2009 and according to the municipality of The Hague [101] the heat recovery system is designed to reduce CO_2 emissions up to 50% compared to conventional heating systems.

Another case study in the Netherlands uses a shallow pond (0.4 m deep, 350 m long, and 32 m wide), constructed for aesthetic purposes, functions as a solar energy collector to regenerate an ATES system. The total complex is constituted of 1200 apartments, distributed over 10 buildings along the pond and other 9 buildings around it. The heat supply of the complex is carried out by a heat pump that takes thermal energy from warm and cold wells 300 m away from each other [102]. In order to compensate the heat extraction during winter, the solar energy captured in summer by the pond is transferred to the ATES. In addition, the system consists of a fountain, a buffer tank to equalize the temperature of the water from the pond during the day, two more ponds for water transportation and a plate heat exchanger. The cold wells have an average temperature of 7 °C while the warm wells are kept at 15 °C. The pond can capture 36 TJ of thermal energy in summer. In Europe, in the year 2006 there were approximately 110 operating projects of district cooling representing 1% of the total cooling capacity of the continent [103].

Cold recovery from shallow lakes is a competitive option to replace conventional air-air cooling systems in warm weather urban areas of Turkey [104]. This is partly due to the water temperature being more stable compared to air temperature in warm seasons especially when peak cooling loads are required. In addition, although water pumping can reduce the COP up to 25% when there is a long distance from the water source to the consumer, auxiliary equipment used in water-to-air heat pumps for cooling consumes less energy than conventional air-to-air heat pumps (COP of water-to-air heat pump is 15–40% higher).

A method to design cooling systems in warm climates based on ground and surface water is described by Kavanaugh [105]. The author considers that key procedures are the proper matching of the heat pump with the water circulation system, the calculation of heat/cold demand and energy consumption of auxiliary equipment. Water from deep ponds is being used for cooling some offices located in the south east of Amsterdam. In that project, an energy company operates a system which subtracts cold water from the bottom of a lake. Phosphate is removed during treatment (in charge of the municipal water company) to avoid eutrophication. The water enters into a heat recovery system where the cold water is used for cooling and the warmer water goes back to the lake. With this technology the energy consumption for cooling in the building compared to individual cooling machines has been able to be reduced six times [106]. Newman and Herbert [107] presented two more case studies of cooling systems from deep water in Toronto and Halifax in Canada.

5. Factors influencing heat reclamation projects in the UWC

5.1. Heat loss during transportation in heat recovery systems

In thermodynamic terms, urban water – or wastewater – networks are open systems, whilst there is interaction with the surroundings. The water transported through pipes tends to have a similar temperature as the ground and heat is dissipated through the wall pipes [108]. Therefore, if heat is to be recovered, the distance between the user and the heat source is of importance. It has been observed that after 10 km of transport in main sewer pipes, wastewater has the same temperature as the soil [47]. This length will be reduced when the pipes and flow are smaller since there will be more transfer are per mass flow. Funamizu et al. [58] have described some equations to calculate the heat loss due to transportation of warm water along the distribution network.

An urban water heat recovery system can be divided into two parts: the section where heat is extracted (independently of the source of heat) and the heat distribution network. Fig. 4 represents

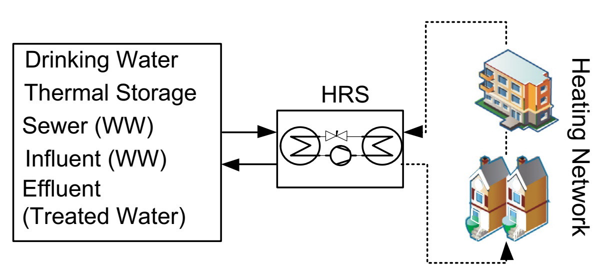

Fig. 4. Different heat sources of an urban water heat recovery system.

both sections. Continuous lines correspond to a heat extraction section while dotted lines resemble a heat distribution network.

Currently, there are few publications which describe methods to calculate the heat that will be lost during water transportation in drinking water and sewage networks. Sallanko and Pekkala [109] made an empirical calculation of the temperature decrease in pressurized sewer lines by measuring the temperature in several sewer pipes of different capacities (150 to 800 m^3/d) in a rural area in Finland. The authors found that the temperature decreased at a rate of 0.16 to 0.27 °C/km in the beginning of the pipes and at the end of the pipes, the average decrease rate was 0.02 to 0.10 °C/km resulting in an average temperature range from 14 to 4.0 °C, which affects the biological processes at the WWTP. Waneer et al. [110] presented a mathematical model to estimate the temperature of partially-filled sewer pipes which was improved and included in a software developed by Dürrenmatt and Wanner [108]. The software was tested in a case study where the difference between the predicted and the experimental temperature was approximately 4 °C. Hendron et al. [111] simulated the heat loss when water was transported inside households constructed with different types of materials. The results lead to the conclusion that for a household with isolated walls, heat loss due to water transportation is not significant (1% of heat loss). The results obtained in the study also suggest that isolation in warm climates increased the heat consumption because solar radiation can pre-heat the pipelines before tap water consumption.

5.2. Consequence of heat recovery on the performance of a WWTP

If heat is extracted from the sewer, the wastewater temperature will decrease. Cold wastewater temperature may affect the biological processes of a WWTP.

A WWTP was monitored in Switzerland during episodes of rain in winter, in order to study the effects of low temperatures in the biological process. It was observed that when there was a quick drop in temperature for a couple of hours (rain episodes), the hydraulic retention time acted like a temperature buffer in the tanks resulting in a stable biological process [92]. Nevertheless, the authors mentioned that when there was a continuous temperature drop (e.g. in the case of long rain periods), 1 °C drop in the mixed liquor temperature decreased the nitrification rate by 10%. Operationally, the nitrification could be controlled by adjusting the sludge retention time.

For regulatory purposes, a German rule applicable for the design of single-stage activated sludge plants (ATV-DVWK-A 131) dictates that the sludge retention time (SRT) in nitrification must be corrected in function of the activated sludge temperature taking into consideration a safety factor (SF) that relates the WWTP size and the biochemical oxygen demand (BOD) load. A SF of 1.8 is good for WWTPs with 1200 kg_{BOD}/d (20,000 population equivalents) while a SF of 1.45 requires five times the influent loads (6000 kg_{BOD}/d or 100,000 population equivalents) as is shown in Eq. (1) [112].

$$\mathrm{SRT} = \frac{\mathrm{SF}}{(0.29)e^{0.98(T-15)}} \tag{1}$$

Eq. (1) also regulates any WWTP with nitrification, which influent is previously cooled with a heat recovery system. Different safety factor values can be found inside the applicable German rule for heat recovery systems from wastewater [47]. In agreement with these regulations, to ensure sufficient nitrogen removal, the wastewater temperature must be ≥ 12 °C.

5.3. Consequence of fouling on the performance of sewer heat exchangers

Fouling detriments the hydraulic and thermal performance of any heat exchanger equipment, and must be predicted in order to design and operate equipment accurately [113]. The fouling is associated with nutrients in the water resulting in biofilm growth on the surface of the heat exchanger.

According to Rometsch et al. [69] the heat transfer performance of a heat exchanger (W_A) depends on the heat transfer surface area (A_{HX}) and the mean temperature difference between the heat exchanger medium (ΔT) and a heat transfer coefficient (k) of the heat exchanger. The mathematical relationship is shown in the following formula:

$$W_A = (k)(A_{Hx})(\Delta T) \tag{2}$$

where k is given in W/m^2 K; A, m^2; and ΔT is given in K. The author reports the results of a study where the heat transfer performance of a heat exchanger was plotted against the inverse of k (called fouling factor "f"). A negative natural logarithmic equation could describe the performance affected by fouling with a correlation factor of 80%.

The formation of biofilm can also increase the energy for pumping and decreasing flow, especially in tube-bundle and plate heat exchanger. However, the heat exchanger output can be maintained through increasing the propulsion energy of the heat pump leading to higher temperature differences between wastewater and cooling medium that compensate for lower heat transfer coefficients.

In a survey, the heat exchangers of 28 heat recovery systems were examined. In all cases, biofilms and deposits on the surface lower the heat transfer [67]. The studies concluded that the concentration of certain wastewater components is the dominant factor for heat exchanger defilement. Particles like sand, gravel and leaves form sediments with lower flow velocities may clog the heat exchanger surface area. Organic substances and nutrients promote the formation of a few millimeters biofilm. Inorganic substances can react to insoluble components that precipitate and interfere with the heat exchange process. In Table 4 a summary of the case studies, heat exchanger types, cleaning methods and performance of the heat exchanger is presented.

In the worst cases, the transfer efficiency can be reduced to 40% of its original performance although it is common to find reductions

Table 4
Study cases, types, cleaning method and performance of sewer heat exchanger surveyed by Wanner [67].

Source of heat	No. of cases	heat exchanger type	Cleaning method	Size	Frequency	Observations
Sewage	10	Canal	Not cleaned, mechanical, high pressure		Monthly—Every 6 months	Cleaning depends on turbulence and brunching, wastewater quality. Over dimensioning the heat exchanger prevents clogging.
Effluent	9	Bundle tube	Pressure, mechanic, chemical rinse*		Monthly (Mechanical)—Every 2nd year (Chemical)	heat exchangers with effluent in the outer part are less affected by fouling. Bio fouling can cause 50% less heat transfer.
Effluent	9	Plate	Mechanical, automatic rise chemical	1.6–40 mm distance	Daily (self-cleaned), —Yearly	Cleaning frequency is independent of plate distance, but depends on pretreatment. With more distance heat exchangers are less affected by fouling. Fouling can cause 25–60% less heat transfer.

near 30% [67]. In one case, a more than 20- year-old heat recovery installation in Switzerland was designed with an over-dimensioned (30%) heat exchanger to assure proper function of the system [78]. Periodic cleaning can recover 20% of the heat transfer efficiency [94]. Materials of heat exchangers can play an important role; copper can prevent an excessive biofilm formation and the use of this metal has been patented [114]. The use of high pressure nozzles to clean pipe heat exchanger has been documented [69].

Although a heat exchanger can be simple in its design, the type of equipment could largely influence the feasibility of a heat recovery system because the materials for construction, its installation (sometimes they have to be installed beneath the streets or prebuilt caverns), size and number of elements as well as the efficiency decrease due to fouling play an important role regarding the costs of a heat recovery system. Constructors emphasize the importance of this equipment when they talk about experiences. That is why continuous cleaning is essential for the good operation of the heat recovery system.

6. Discussion and recommendations

In the first part of Section 3, an energy balance to operate the urban water cycle of some regions of the world was presented. The balance showed that 80% of the energy is spent by the end-user mainly in heating while the remaining 20% is used in waterworks for treatment and transportation (of raw water, drinking water and wastewater).

Subsequently, some examples to reduce the use of energy from fossil fuels were mentioned in an order proposed to minimize the consumption of this type of energy. In relation to water and wastewater facilities, there is available information about successful cases where waterworks have reduced their consumption by the improvement of their equipment and practices to the point that they have become energy producers instead of energy consumers. However, the number of references about study cases where the energy consumed by the end-user has been reduced or reused are fewer in number, they come from a limited amount of countries, and most of them talk about heat recovery from wastewater for water preheating of ambient heating. Since the energy spent by the end-user represents the largest expenditure (of energy) in the water cycle, many efforts should be focused on reducing its consumption.

The authors of this manuscript consider that in spite of the existence of technology to reuse energy from water, it has not been spread worldwide for various reasons:

- The available technology allows obtaining low-quality energy which can be used for few purposes. Therefore, ambient heating and cold water preheating have been the two main solutions to the recovered heat. In this sense, there is a necessity to carry out research on more applications of the recovered heat (or cold). In this way, more approaches can be found for heat recovery in places where ambient heating is not needed.
- Along a whole year period, when there is no need for ambient heating, a heat recovery system could store the heat in a storage facility. However, the possibility for the installation of such feature depends on the specific site of implementation. Research is needed to study approaches to equilibrate the spatial and time mismatch of demand and supply as well as energy storage methods that can be coupled with recovery systems of low-quality heat. Concerning the use of heat exchangers in households, there is still little scientific knowledge about the performance of heat exchangers in a long time period and with different use conditions.
- The economic feasibility of heat recovery systems is a key factor for its development. The costs of installations are higher when new infrastructure has to be built; this situation restricts the implementation of heat recovery installations to new developments or places where a major sewer renovation is planned. In addition, the competitive price of fossil fuels compared with renewable fuels has caused projects to depend on subsidies. Therefore, there is a need of knowledge of financial approaches to make energy recovery from water attractive and competitive compared to other renewable sources.
- In relation to the performance of heat recovery systems, there is relatively little independent information available. Because the market is small, there are only few competitors and they are concentrated in specific countries. Much of the successful case studies have been published by the same companies which could tend to emphasize the positive issues of the technology. There is a need for independent information about case studies, experiences, technical problems, social acceptance, and interaction between the stakeholders that have used this technology. How have heat recovery systems been developed in other economies different than those mentioned in this paper and in other climatic conditions and a variety of situations? These are questions for future research.
- Most of the case studies presented in this review have in common that they were installed in main sewer pipes where a continuous flow is guaranteed and the heat consumer was also near the heat source. In some cases, the heat withdrawn from the heat source should decrease the water temperature by only a few degrees Celsius because of the risk of affecting the biological process in a wastewater treatment plant. However, some new constructions and renovations are not big enough to guarantee continuous flow and heat consumption over long periods of time. Many of them are far away from wastewater treatment plants and during transportation, the temperature of the chilled water will be affected by the soil temperature and other tributaries that would minimize the risk of a cold influent. In that case, every potential project has specific requirements in size, consumption pattern, heat storage (or energy offer–demand mismatch), downstream risks, that should be evaluated specifically. Information concerning approaches to detect susceptible points to install small-size heat recovery systems is needed. Modeling tools would help to estimate the available heat in places where a renovation or new construction is planned, to predict the impact of colder water in the stream to the waste water treatment plant, and to calculate the energy balance between heat offer and demand of a heat recovery installation in long term scenarios.

7. Conclusions

The two main types of energy used in the urban water cycle are electricity and heat; the latter can represent 80% of the primary energy expenditures related to water use in the residential and commercial sector. In the Netherlands, the equivalent CO_2 produced in the UWC represents more than 3% of the total CO_2 produced per inhabitant. This amount could be higher if the methane in the sewer network is included in the balance.

Some actions to reduce the total expenditure of energy from fossil fuels used in Urban Water include:

- Synergic measures to save water and energy in urban zones such as the installation of water-saving head showers and toilets, installation of tap flow regulators, leakage minimization, water consumption advice and water demand management.
- Substitution of fossil fuels used in the urban water cycle for renewable energy sources.
- Extraction of energy from urban water.

- Optimization of processes in water facilities, specially the high energy intensive processes.

Simple equipment such as heat exchangers installed in domestic appliances or beneath the shower, is the first approach to recover heat from households. The installation in already constructed buildings can be costly, though. A big advantage when using this equipment is that the demand is almost synchronized with the heat offer and the heat source is close to the place of consumption.

Space heating is currently the largest use of heat from urban water. Equipment used for its extraction are heat pumps, heat exchangers and heat storage installations. Published literature enumerates several successful projects of heat recovery mainly from wastewater although there are reports where sea water, ponds and lakes were used. Most of the study cases are located in Switzerland and Germany. The heating capacity of heat recovery system varies from 100 to 16,000 kJ/s. Another reported use of water as energy source is to melt snow and to use it as a coolant.

Some reported factors that influence the process of heat recovery systems from sewer networks are:

- The energy losses during the transportation of recovered heat to the consumer. A model to determine how much heat is lost in the sewer during transportation and potential would help to assess the feasibility of projects more accurately. Suitable spots to install heat recovery systems could also be identified with modeling tools.
- The consequence of heat recovery installations in wastewater treatment since it is the influent of WWTPs. If the heat is extracted in this zone, the biological treatment could have problems especially in the nitrification process.
- The biofilm formation. It has been shown that microbial growth in heat exchangers can reduce their efficiency up to 40% and also increase the energy consumption for pumping. Regular cleaning of the heat exchangers (especially in wastewater) should be done to avoid thick layers of biofilm formation.

In conclusion, although some successful examples of heat recovery from urban water have been mentioned, the recovered energy is still minimal compared to the total energy available in urban water.

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